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Ionization-induced generation of strong Langmuir waves by high-intensity Bessel beam

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Dynamics of the field and plasma at the gas breakdown produced by the Bessel (axicon-focused) laser beam is studied with the effects of natural plasma waves generation and reflected wave spectrum conversion taken into account

We study in this paper the dynamics of the field and plasma in the discharge column created by axicon focusing [1-3] of a high-intensity laser radiation in homogeneous gas. We focus on the effect of natural plasma waves generation considered previously for other types of the optical and microwave discharges [4, 5].

The spatiotemporal evolution of the electric field $\tilde{\mathbf{E}} = \text{Re}[\mathbf{E}(\mathbf{r}, t) \exp(-i\omega t)]$ is calculated numerically based on the vector wave equation for the slow time envelope of the field $\mathbf{E}(\mathbf{r}, t)$:

$$\frac{2i}{\omega} \frac{\partial \mathbf{E}}{\partial t} + \delta^2 \nabla (\nabla \cdot \mathbf{E}) + \epsilon \mathbf{E} - \frac{1}{k_0^2} [\nabla \times [\nabla \times \mathbf{E}]] + \hat{\Gamma} \mathbf{E} = 0 \quad (1)$$

This equation takes into account the spatial and time dispersion and allows us to describe the processes of resonance excitation and Landau damping of Langmuir waves in the time-varying plasma. In Eq. (1), $\hat{\Gamma}$ is the model dissipation operator: $\hat{\Gamma} \mathbf{E} = -i a \delta^2 \nabla (\nabla \cdot \mathbf{E})$, $\epsilon = 1 - (N/N_c)(1 - i\nu/\omega)$ is the complex permittivity of the plasma, $N_c = m(\omega^2 + \nu^2)/4\pi e^2$ is the critical density, ν is the electron collision frequency, a is the coefficient of order unity, $k_0 = \omega/c$, $\delta = \sqrt{3} V_T / \omega$, $V_T \ll c$ is the thermal electron velocity.

Gas breakdown is caused by the optical-field-induced ionization processes. As an example we consider tunnel ionization of hydrogen atoms and determine the time averaged ionization rate by the known expression

$$\frac{\partial N}{\partial t} = 4\Omega (N_g - N) \sqrt{\frac{3E_a}{\pi|\mathbf{E}|}} \exp\left(-\frac{2E_a}{3|\mathbf{E}|}\right). \quad (2)$$

Here $E_a = 5.14 \times 10^9$ V/cm and $\Omega = 4.16 \times 10^{16} \text{ s}^{-1}$ are the atomic field and frequency units, and N_g is the concentration of neutral atoms before the process of ionization. The parameter range we are interested in here is the following: the wavelength $\lambda \sim 0.6 - 10 \text{ } \mu\text{m}$, laser pulse intensity $S \sim 10^{14} - 10^{16} \text{ W/cm}^2$, and the gas pressure $p \sim 0.3 - 70 \text{ atm}$.

We consider the model of the axially symmetric discharge: $N(\mathbf{r}, t) = N(r, t)$ produced by the rotating cylindrical wave with the complex envelope of electric field $\mathbf{E}(\mathbf{r}, t) = \mathbf{E}(r, \phi, z, t) = \mathbf{E}(r, t) \exp(i\phi + ik_0 z \cos \theta)$ (r, ϕ, z are the cylindrical coordinates). Outside the

plasma ($r \geq R$, $N(r \geq R) = 0$) the field is a superposition of the converging (incident) and diverging (reflected) TE and TM waves with a given angle of inclination θ to the axis of symmetry z . The incident wave is given by the axial components of electric and magnetic fields: $E_z^{(in)} = C(t) H_1^{(2)}(k_0 r \sin \theta)$, $H_z^{(in)} = -i \cos \theta E_z^{(in)}$, $C(t) = A \exp(-(t-t_0)^2 / \tau^2)$, $H_1^{(2)}$ is the first-order Hankel function describing the converging wave. The correlation between the amplitudes of these components (the coefficient $-i \cos \theta$) is chosen so that the transversal components of the fields in the absence of plasma are circular polarized and are the zero-order Bessel function of radius r : $E_\phi(r) = i E_r(r) \sim J_0(k_0 r \sin \theta)$. We note that, in the presence of plasma, the field remains circularly polarized only on the axis.

Equations (1) and (2) were solved numerically in the space interval $0 \leq r \leq R$ with the initial conditions: $N(r, 0) = 0$, $E_\phi(r, 0) = -2C(0) \cot \theta J_0(k_0 r \sin \theta) = i E_r(r, 0)$, $E_z(r, 0) = 2C(0) J_1(k_0 r \sin \theta)$ and the following boundary conditions: (i) the solution is analytical at $r = 0$: $E_z = 0$, $\partial E_{r,\phi} / \partial r = 0$, (ii) all field components (including E_r) are continuous at $r = R$ (for detailed expressions and explanation see [6]).

It has been found that the scenario of the breakdown process depends greatly on the convergence angle of the wave. If this angle is less than some critical value $\theta_c \approx 25^\circ$, the maximum plasma density $N_{\max} \sim N_c \theta^2$ that is less than the critical one. However, at the angle exceeding the critical one, the plasma density at the axis increases in the sharpening regime and passes the critical point, after that the fast ionization wave containing the plasma resonance point at the leading front propagates in the radial direction. The results of numerical calculations are presented on Figs. 1 and 2 in dimensionless variables $k_0 r \rightarrow r$, $\omega t \rightarrow t$, $\mathbf{E}/E_a \rightarrow \mathbf{E}$, $N/N_c = n$ for the parameter values: $\theta = 30^\circ$, $\Omega/\omega = 22$, $k_0 \delta = \sqrt{3} V_T / c = 0.02$, $\nu/\omega = 0.01$, $a = 0.1$, $N_g = 1.5 N_c$, $t_0 \omega = 100$, $\tau \omega = 50$, $A/E_a = 0.0204$, $k_0 R = 4$. At the given values of A , the maximum field at the axis in the absence of plasma

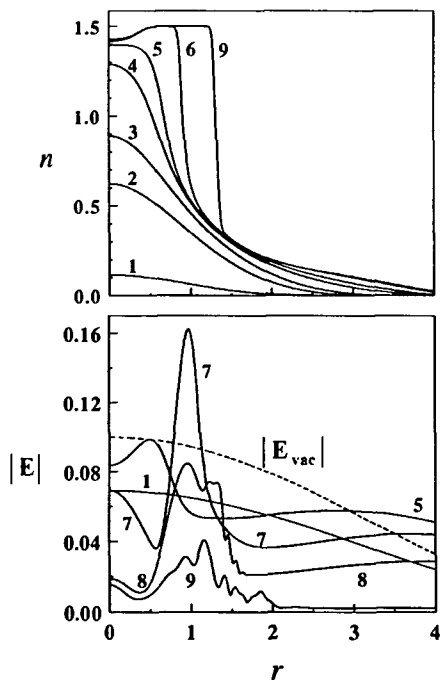


Fig. 1. Evolution of the plasma density $n(r,t)$ and the field amplitude $|E(r,t)|$ at $\theta = 30^\circ$. Curves 1-9 correspond to the time instants $t = 80, 90, 95, 105, 110, 120, 130, 150$, and 200 , respectively. The dashed curve shows the unperturbed field $|E_{vac}(r)|$ (in the absence of a plasma) at $t \approx t_0 = 100$.

is the same: $|E|_{\max} / E_a = 0.1$. The above dimensionless parameters correspond to the vacuum wavelength $\lambda \approx 0.8 \mu\text{m}$, maximum pulse intensity $S \approx 3 \times 10^{14} \text{ W/cm}^2$, pulse duration (at the level of $1/e$) $\tau\sqrt{2} \approx 30 \text{ fs}$, and the gas pressure $p \approx 60 \text{ atm}$.

The transition of the plasma density through the critical value at $\theta > \theta_c$ (Fig. 1) is accompanied by the excitation of intense Langmuir oscillations, whose amplitude reaches its maximum (twice as high as the amplitude of the unperturbed electric field at the axis) at the front of the ionization wave at $r = 1$.

The coupling of the excited Langmuir oscillations to an external electromagnetic field (due to the presence of a fairly sharp boundary of the ionized region) gives rise to the partial emission of their energy into the surrounding space, i.e., to the occurrence (along with the fundamental frequency component ω) of one or several components at frequencies close to $\omega_{p\max} =$

$\sqrt{4\pi e^2 N_g / m} \approx 1.22\omega$ in the spectrum of the cylindrical wave reflected from the discharge. In view of the linear character of the "transition" resonant excitation of Langmuir oscillations, the intensities of the shifted spectral components are proportional to the intensity of the incident wave. This linear parametric conversion of

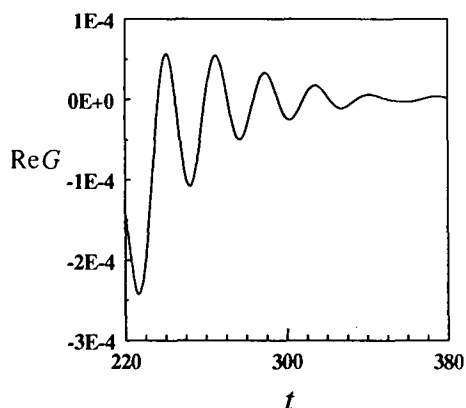


Fig. 2. Time behavior of the amplitude function $\text{Re}G(t)$ of the reflected TE wave at large times. The curve illustrates the radiation from the discharge at the upshifted frequency $\omega_{p\max} \approx 1.22\omega$.

the scattered spectrum of an ionizing electromagnetic wave (previously described in the model of a thin gas slab [5]) is illustrated in Fig. 2 by the time dependence of the quantity $\text{Re}G(t)$ determining the amplitude of

H_z -component of the reflected wave $H_z^{(r)} = G(t)H_1^{(1)}(k_\perp r)$ at large times $t > 220$ (after the end of the incident pulse), when the signal amplitude at the fundamental frequency has already substantially decreased, but the Langmuir oscillations still exist and continue emitting. The transversal wave number at the frequency $\omega_{p\max}$ is $k_\perp = (\omega_{p\max}/c) \sin \theta_p =$

$\sqrt{(\omega_{p\max}/c)^2 - k_0^2 \cos^2 \theta}$, that is the corresponding reflected cylindrical wave is inclined to z -axis at the angle $\theta_p > \theta$ ($\cos \theta_p = (\omega/\omega_{p\max}) \cos \theta$). In the given numerical example, $\theta = 30^\circ$, $\theta_p = 45^\circ$; at $t \approx 250$ the intensity of the frequency shifted component is about 10^{-4} of the maximum intensity of the incident wave.

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References

- [1] L.Ya. Margolin *et.al.*, Sov. Tech. Phys. Lett. **13** (1987) 89.
- [2] H.M. Milchberg *et.al.*, Phys. Plasmas **3** (1996) 2149.
- [3] A.A. Babin *et.al.*, Physics-Uspekhi **42** (1999) 74.
- [4] V.B. Gildenburg and N.V. Vvedenskii, Phys. Plasmas **8** (2001) 1953.
- [5] M.I. Bakunov *et.al.*, Phys. Plasmas **9** (2002) 2803.
- [6] N.V. Vvedenskii and V.B. Gildenburg, JETP Lett. **76** (2002) 380.